The Physics Teacher

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Cognitive Research–What's in It for Physics Teachers?*

By Jose Mestre and Jerold Touger

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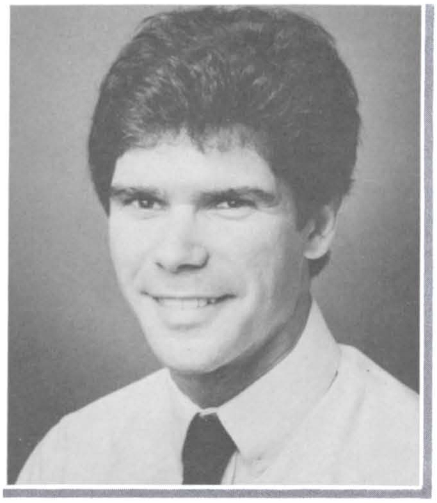
Within the last 10 to 15 years, a growing number of cognitive research studies have reported on the thought processes underlying effective learning and problem solving in physics. These studies have yielded a number of important findings, many of which have direct implications for classroom instruction. And yet our strong impression is that many teachers are unaware of what these studies tell us. This is unfortunate, but perhaps not surprising. To mention only one obstacle, there have been few channels of communication through which teachers could hear of this research as a matter of course. In the past few years, the American Association of Physics Teachers (AAPT) has become one such channel through its highly successful Physics Teacher Resource Agents (PTRA) program and workshops sponsored by its Committee on Research in Physics Education. However, it is not yet clear to what extent research findings are disseminated by these means, and articles on the findings frequently fail to reach a broader audience of physics teachers. Papers reporting research too often appear in journals or are presented at conferences where the predominant audience, both intended and actual, is other researchers. Most critical is the fact that the teacher's everyday tools – the textbooks and the teacher's guides that accompany them – remain essentially untouched by the research.

There are important reasons for trying to break this closed circle. One is the increasing certainty we have about the implications of some of these research findings; another is the impact they can have on physics teaching. By now, we all know of the strong pressure on teachers to help their students become "inquirers" and "problem solvers" and, in doing so, to de-emphasize the memorization of large amounts of factual information that has been such a prevalent pursuit in our schools. There is little dispute that some shift in emphasis from content to process is a very desirable change of direction, but it is not clear how to accomplish this goal unless we first understand the student as a learner and then translate our understanding into improved teaching practices. To make headway we need not just communication, but also close cooperation between cognitive researcher and classroom teacher. In fact, it is often both possible and valuable for the teacher to *be* the researcher in his or her own classroom.

In attempting to work toward common ground, we will comment very briefly on the nature of cognitive research in general, and then focus on those areas of research that we believe to be of special interest to classroom physics teachers.

What is Cognitive Research?

Much of cognitive research is concerned with issues underlying knowledge acquisition and use. In dealing with



***Jose Mestre** received his Ph.D. in nuclear physics from the University of Massachusetts, where he is now associate professor of physics. For the last ten years he has been engaged in cognitive studies of problem solving. His recent research interests focus on how experts and novices acquire physics knowledge and store it in memory and on how they use this knowledge in problem-solving situations.*

a scientific domain such as physics, it attempts to understand the process of thinking and learning. Fred Reif[1] has described education, as it occurs in and out of the classroom, as a process that produces a transition between some initial state of the student's knowledge and some desired final state. Cognitive research must try to understand the nature of the initial state (the student as he or she enters our class), the process of teaching and learning by which a transition can be brought about, and the nature of the goal state, which ideally is expertise (though we almost always settle for less).

In the remainder of this paper, we discuss two areas of increasing importance in cognitive research and their implications for the classroom. The first addresses the "initial state" of the learner and involves what the research literature refers to as "misconceptions" that students bring with them to (or even develop in) their physics classes. The second, which considers the goal state as well, deals with different ways that novices and experts go about storing and accessing information and solving problems.

Misconceptions Research and Some Implications

Educational theories change, but over the years one can detect a persistent assumption that students come into physics classrooms with "clean mental slates," and that learning, therefore, can begin from a zero point (Fig. 1). Thus, when students do not learn as much as expected, the simple belief might be that the difficulty can be overcome by making the presentation of the material either more lucid or more insistent. This implies that what is to be learned should fairly readily take hold, for there is supposedly nothing present in the student's mind (if it is paying attention) to resist or fight against it.

Recent findings from cognitive research, however, make this assumption untenable and should persuade us that instruction cannot be based on any notion that implies the absence of prior knowledge in the minds of students.

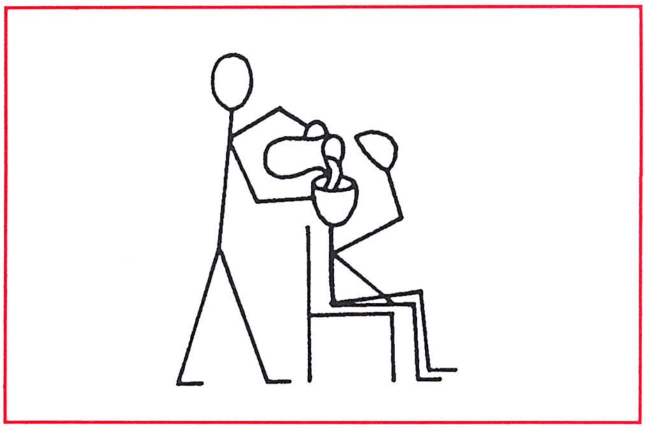
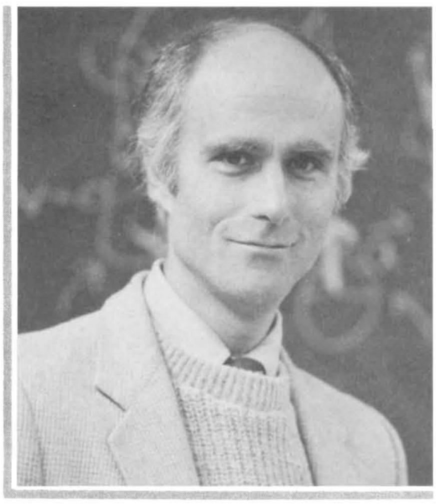


Fig. 1. The clean slate or empty-vessel theory of education.

Research shows, in fact, that students usually bring what might be called "naive theories" (also termed "spontaneous conceptions") to their dealings with the phenomena of physics. These theories are ones that they—and everyone—arrive at as part of living in the world and making sense of what happens around us. As thinking beings, we are naturally inclined to explain, categorize, and order events so that they make sense to us. The result is that during the course of our lives we actively, albeit unconsciously, construct simple or "common sense" theories that provide us with explanations of the world and its phenomena.[2] This natural inclination is crucial to all learning.

The problem arises because these "naive theories" often tend to include misconceptions that interfere with students' ability to understand concepts presented in the classroom, and this interference usually occurs regardless of how clearly teachers present concepts. Moreover, these misconceptions retain a stubborn hold on students' thinking. Investigations to date indicate that they plague learning throughout the sciences and mathematics,[3,4] but the research is particularly rich in physics, from which we draw the following examples.



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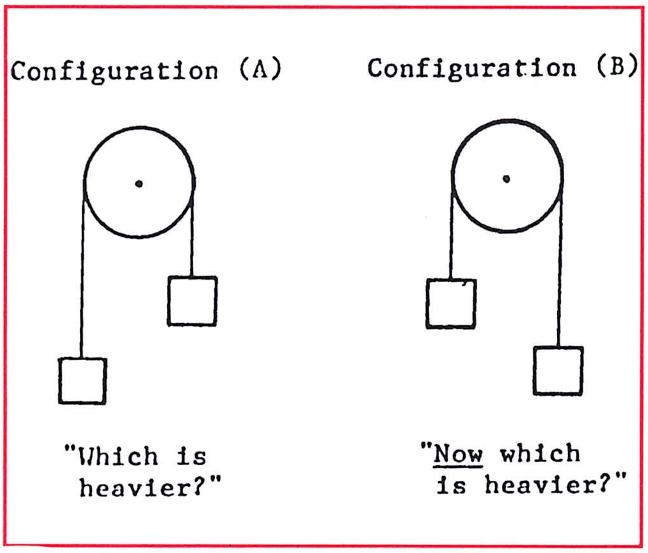

Fig. 2. Atwood's machine can be used to demonstrate student misconceptions.

- The first concerns the Atwood's machine set-up in Fig. 2, which can be made the basis of a class discussion or a one-on-one interview. Blocks of equal mass are suspended from opposite ends of a rope hung over a pulley. The blocks are placed in Configuration A in Fig. 2, so that they remain stationary with the left block hanging lower. When students are asked, "Which block is heavier?" many will choose the lower one. This misconception is easily confronted. Change the set-up to Configuration B in Fig. 2, likewise a stationary arrangement, and ask "Now which is heavier?" The idea here is to challenge the student's erroneous conception not by explaining it away but by creating a contradiction and asking the student to resolve this contradiction with guidance in the form of probing questions from the teacher.
- A second recurrent misconception concerns curvilinear motion. Many students who have done well in a college physics course may still describe incorrectly the motion of an artillery shell after it is fired from a tank turret that is rotating. A typical incorrect description states that, when viewed from above, the path of the airborne shell continues to curve sideways in the same general direction as the turret's rotation. The misconception derives from a mental model attributing to the shell an ability to "remember" that it was moving in a curved path while inside the barrel. (See Reference 5 for a recent treatment of curvilinear misconceptions.)
- Yet another common misconception concerns the forces acting on a batted baseball while it is in the air. Many students incorrectly claim there are three forces acting on the airborne ball: the gravitational force, a drag force due to air resistance, and the "impact force" that the bat imparted to the ball. Newtonian physics only acknowledges the first two of these. Students asserting the existence of an "impact force" view it as an attribute possessed by the ball as a result of its contact with the bat, as opposed to the mechanism by which the bat imparts an initial speed and direction to the ball. (Note the similarities between this and the previous example.) There is a possible carry-over here from the lack of distinction in everyday language between "it struck with great speed" and "it struck with great force." In fact, evidence that students associate force with velocity, and even

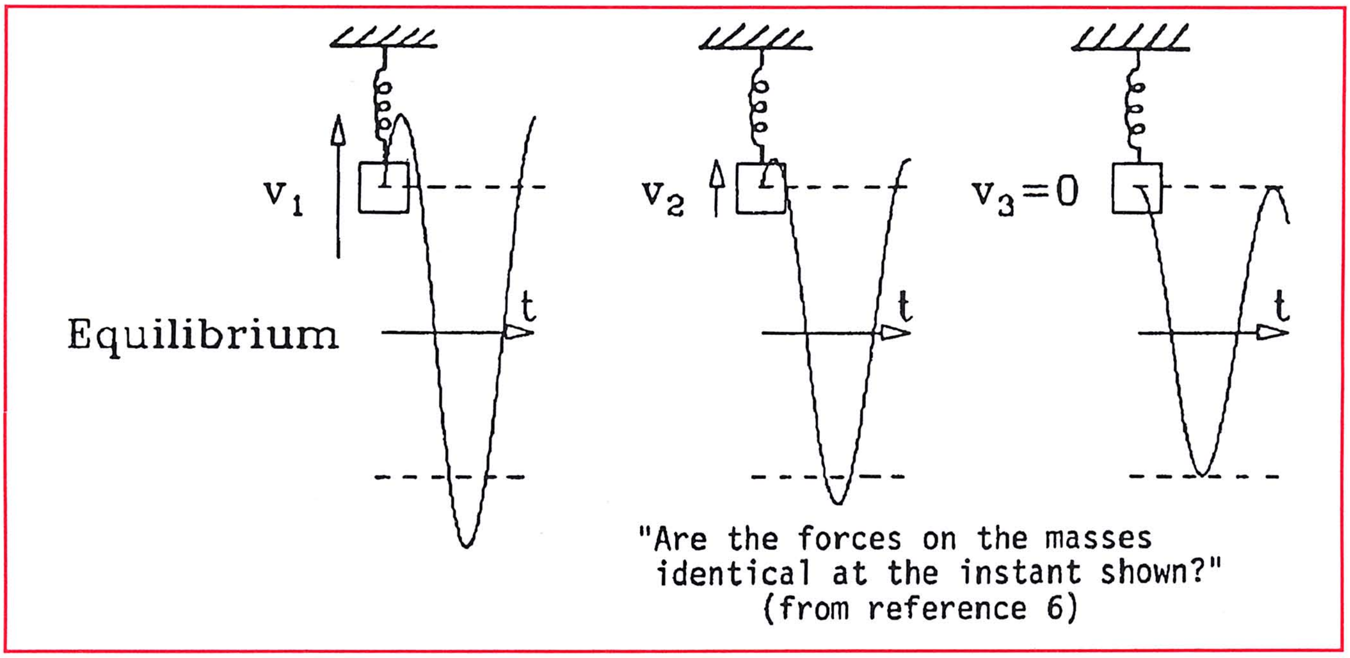

Fig. 3. This pencil-and-paper demonstration, drawn from Reference 6, shows that students hold the misconception that force is related to velocity.

view it as proportional to velocity rather than acceleration, has been provided by studies such as one using the pencil-and-paper test shown in Fig. 3.[6] Stronger students may also hold these misconceptions and are able to reason more elaborately from them. (For example, if force is proportional to velocity, and objects accelerate during free fall, then there must be a gravity gradient.)

- Misconceptions in physics are not limited to mechanics. In electricity, students often consider a battery to be a source of charge rather than voltage. When presented with the circuit in Fig. 4, students will usually recognize that if R1 is increased, the bulb dims. But many will argue that if R2 is increased, the bulb is unaffected because the charge has already passed the bulb.[7] In kinetic theory, many students will argue that the reason the pressure exerted by a gas in a rigid closed container increases with temperature is that the gas (or molecules) "wants to expand." Although they accept that molecules move faster at higher temperatures, the notion of expansion overrides the need to seek a specific mechanism (e.g., molecules striking the walls more frequently at greater mean velocity) for increased pressure. Misconceptions in optics were discussed by Goldberg and McDermott in *TPT* and *AJP* articles.[8]

Other examples of misconceptions abound in the research literature. Some excellent reviews[9,10] and bibliographies[11-13] provide a fuller guide for the interested reader. The fact that interest in this field remains robust is reflected in the heavy attendance at two international conferences on misconceptions held at Cornell University in 1983 and 1987, with the latter meeting yielding three large volumes of proceedings.[4]

It bears repeating that clear presentations by teachers do not in themselves eradicate existing misconceptions and replace them with correct ideas. Several studies point this out.[2,8,9] Misconceptions, by virtue of the fact that individuals have spent time and energy constructing them, often turn out to be deeply seated and difficult to dislodge. We should bear in mind that what physicists think of as a misconception may seem plain common sense to many people.

So simply telling students that their conceptual understanding is wrong or incomplete, and combining this with a correct explanation, is often not sufficient for eradicating most misconceptions. Cognitive studies show that misconceptions are tenacious, and even their seeming elimination is often followed by a resurfacing of the same misconception in a student's work a short time later.

What This Suggests About Classroom Teaching

One obvious implication of misconceptions research for classroom teaching is that instruction will often be ineffectual if it does not address the prior ideas of students. This indicates that the educational process must become more bidirectional than it is now. In other words, physics teachers should help students articulate how they think about a problem being studied and, in doing so, be alert to misconceptions that students may bring to the surface (and tenaciously defend). These misconceptions should then be openly addressed, as opposed to teachers simply making lecture-style presentations of correct approaches. Unless this give and take occurs, it seems highly likely that misconceptions will interfere with "the message" and that what is said by the teacher will not be equivalent to what is heard by the student.

Because misconceptions can be so resistant to change, it also seems important that students participate actively in the process of overcoming them. A technique some have found effective involves helping students to confront an inconsistency or contradiction between their assumptions and actual physical behavior. We saw a simple instance of this in the case of the Atwood's machine discussed previously. Once the student perceives the inconsistency and accepts the challenge of resolving it, a more promising learning opportunity exists. This process also gives students surer possession of concepts, because it assigns them an active part in reconsidering their prior incorrect understandings and reconstructing correct ones.

Such techniques have taken a variety of effective forms. An approach that has been used effectively in high school physics classes[14,15] involves use of a conceptual "bridge." For example, many students do not believe that a table exerts an upward force on a book that is resting on it. However, they are likely to believe that if you press down on a spring, the spring exerts an upward force on your hand. A set-up involving a conspicuously springy table can bridge the gap between the two analogous (i.e., analogous to the physicist) situations. In an impressive demonstration that reinforces this point,[16] a mirror is mounted on a seemingly rigid body such as a cinder-block wall. A laser

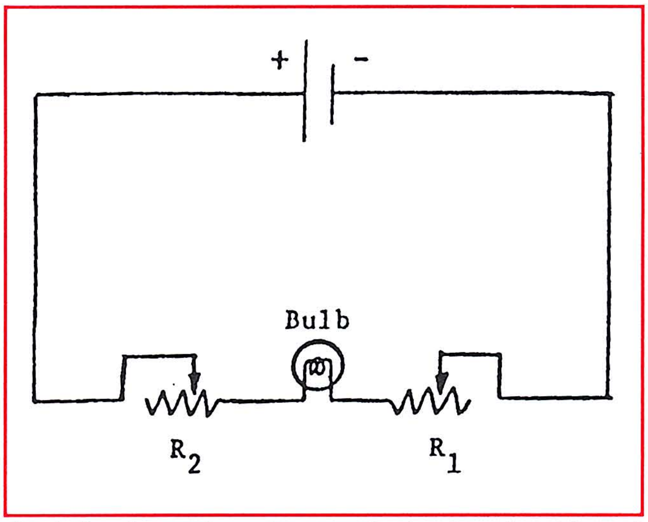

Fig. 4. Another student misconception involves electricity and the voltage of a battery.

beam is reflected off the mirror to a photocell connected to an audio amplifier, from which it is reflected back along its original path to the laser. When the wall is pressed, the net signal resulting from the interference of incident and reflected beam varies at audio frequencies, and the springiness of the so-called "rigid" body is made audible.

Innovative demonstration equipment can also be used in confronting students' assumptions. Melvin Steinberg[17] gives AAPT workshops showing teachers how to make use of capacitors of enormous capacitance (up to 1.0 farad) in simple bulb circuits, such as that in Fig. 5. Because the giant capacitance prolongs the transition to a steady state when the switch is moved to position B, the transient current from the discharging capacitor lasts long enough to light the bulb. This challenges the misconception we mentioned previously that the battery (now switched out of the circuit) is the source of charge in D.C. circuits.

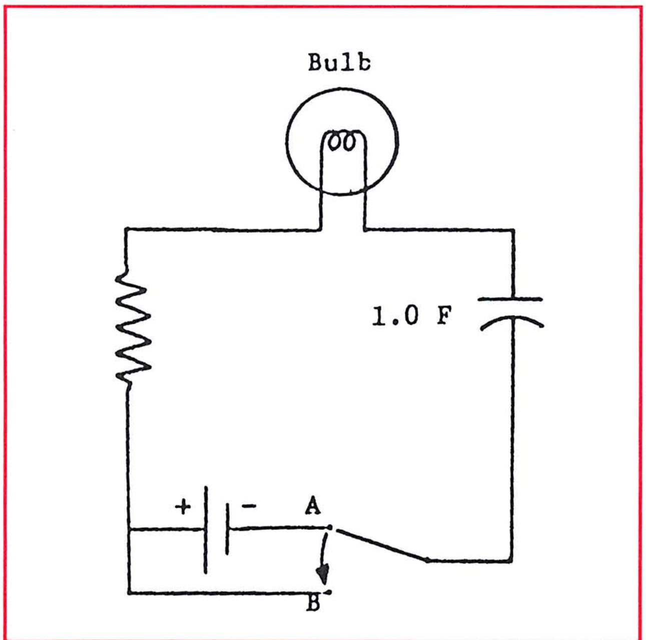

Fig. 5. Student assumptions can be confronted using enormous capacitance in simple bulb circuits.

Computers have also been employed to challenge students' misconceptions by means of games, software, and "microworlds." For example, White and Horwitz[18] designed a microworld called Thinkertools that allows students to explore the principles underlying Newtonian mechanics. This approach synthesizes the learning of the subject matter with the nature and application of scientific laws. These researchers found that sixth graders taught with this approach performed better on a set of force and motion problems than both physics-naive sixth graders and high-school physics students. In particular, the sixth graders taught with the approach learned that an impulse applied to a moving object produces an incremental velocity in the direction of the impulse, and that impulses in one direction have no effect on the velocity component in the orthogonal direction.

In a software-plus-transducer approach, a motion detector feeding to a microcomputer is used to turn the input into graphs of position, velocity, or acceleration vs time.[19] A student's misconception about the nature of the motion represented by any *given* graph can be challenged by aiming the motion detector at the student and asking the student to move in such a way as to reproduce the given graph.

All of these approaches respond to the need to actively engage students in combating their own misconceptions. At this point, however, any classroom teacher might protest, "Fine. But I have 30 students in each of my classes. If I were to address all their individual misconceptions, there would be little time left to cover the material in the course. Besides, I'm not even sure that I know how to get at students' prior assumptions!" These are very valid concerns, but the outlook for having answers is not as bleak as it may appear. The research discussed has consistently revealed that, for a specific topic, a small number of misconceptions account for the majority of errors committed by students. For instance, in the example cited earlier concerning the forces acting on the baseball, it is probable that over 95 percent of all student errors will consist of either omitting one of the two legitimate forces acting on the ball, or of including the fictitious "impact force" on the ball, or both. The number of misconceptions involved in a particular topic for a typical class will generally be fairly small—rarely, we think, more than two or three.

As for identifying misconceptions, there are some fairly natural methods that teachers might adopt:

- Give more attention to speaking and listening in the classroom, and particularly have students verbalize their conceptual understanding of specific topics in qualitative terms. For example, asking a class to speak to the question of forces acting on the baseball will almost guarantee that someone will mention the "impact force."
- Observe error patterns in tests, quizzes, and homework. If the root cause of an error pattern is not clear, the teacher might ask several of the students who committed the error to explain how they arrived at their answers. Many misconceptions go untreated because teachers often view errors in isolation. They are not looking for error patterns that could be explained by correct applications of incorrectly held mental concepts. In beginning to make these observations systematically, the teacher is becoming a researcher on a local scale as part of the teaching process.
- Be aware of your own thinking. Some misconceptions have been observed not only in beginning physics students, but also among advanced undergraduates, graduate students, and both pre-service and (dare we say it!) in-service physics teachers, including university professors. An acquaintance with cognitive research on misconceptions may

provide an opportunity for some teachers to re-examine their own beliefs.

These approaches, if handled well, may also take some of the onus off incorrect answers and help students know what expert physicists know: that thinking one's way toward solutions to problems often meets with difficulty and that correct answers are often built on the recognition of previous error. Indeed, understanding more clearly how experts get the job done is another area in which cognitive research has made a significant contribution—once again, we think, with important implications for the classroom.

Expert/Novice Research and Some Implications

There is a growing body of cognitive research that focuses on how experts and novices perform a variety of tasks and how their approaches differ. "Expert" and "novice" as used here refer, of course, to degrees of skill and knowledge in a specific domain, not to any estimate of general proficiency or success in life. Among recent studies one can find inquiries into expert performance in a variety of pursuits, such as chess,[20] baseball,[21] and computer programming,[22] as well as physics. These studies for the most part attempt to answer two questions: (1) How do experts and novices organize, retain, and use domain-related knowledge? and (2) How do experts and novices go about solving problems? The answer to both these questions seems to be "very differently," and the more we know of the distinctions, the more it appears that they may help us learn how to help students make the transition from beginner to expert more effectively.

Expert/Novice Differences in Knowledge Organization. In physics, as in other domains, it should not be surprising to us that experts and novices organize and retain knowledge in distinctly different ways. If there were few such differences, we could begin to dispense rather quickly with the idea of a beginner. What is surprising, however, is that until recently, we have not inquired closely into the thought processes that make the difference between one who is starting out and one who has arrived at expertise in a specific domain. When we do, the distinctiveness of the expert comes more clearly into focus.

For example, cognitive research discloses that experts gather and store information in clusters or chunks,[23,24] the organization of which can be envisioned as a hierarchical pyramid, with fundamental concepts occupying the highest, most accessible, levels of the hierarchy, followed by ancillary concepts, and with domain-related factual information stored at the lowest level and accessed via reference to more fundamental concepts. Within this hierarchical arrangement, being an expert, or "knowing more," means having: (a) more conceptual chunks in memory, (b) more relations or features defining each chunk, (c) more interrelations among chunks, and (d) effective methods for retrieving related chunks.[25]

These findings bear directly on what we do in classrooms. To cite one example, Eylon and Reif conducted a study[26] in which they asked what happens when novices are helped to organize knowledge, not as it is customarily presented in textbooks and lectures, but rather as it actually exists in the minds of experts. The study asks, if experts organize knowledge in a hierarchical fashion, doesn't it make sense for novices to receive knowledge in a similar form?

To investigate this question, they evaluated the effectiveness of two different modes of presenting a physics argument to college undergraduates—one hierarchical (with calculational details subordinated to main principles that are first outlined to provide overview) and the other more traditional in its organization, involving a single-level description that proceeds step-by-step through calculational details. (One such argument dealt with an experiment in which measurements on a bouncing ball are used to deduce the value of the gravitational acceleration g.)

When tested, those students who received the argument in hierarchical form performed significantly better in both recall and problem-solving tasks than those who received it nonhierarchically. Similar results emerged from a second study, involving a set of rules students were asked to use in a problem-solving assignment. These results indicated that classroom teaching may be more effective when it imparts knowledge in a form that reflects the way experts organize and use knowledge in actual intellectual performance.

Expert/Novice Differences in Problem Solving. Experts also appear to differ markedly from novices in the way they go about solving problems. Cognitive research indicates that experts begin by cuing on a problem's "deep structure" (principles, concepts, or heuristics that could be applied to solve the problem) as the clue to determining which concept(s) or principle(s) should be applied in solving it. They then undertake a qualitative analysis of the problem based on the concept(s) selected. Finally, they take the time to develop a strategy for achieving a solution before they execute procedures for arriving at an answer. In contrast, novices tend to cue on a problem's "surface features" (problem jargon, descriptors of the set-up, etc.), fail to examine its qualitative structure, and plunge toward a solution with little attention given to strategy.

This description emerged from a series of interesting experiments by Chi, Feltovich, and Glaser.[27] They begin by asking what type of cues experts and novices in physics use in deciding how to attack a problem. They pursued this inquiry by assigning the same task to a group of expert physicists and to a group of undergraduates who had successfully completed an introductory physics course. The task consisted of asking the participants to sort a stack of elementary physics problems written on index cards into piles arranged *according to similarity of solution*; that is, problems that could be solved with similar strategies were to be placed on the same pile.

Results showed that the sorting done by novices disclosed a strong inclination toward using surface features to identify and classify problems. For example, novices tended to see problems involving inclined planes as falling in one category, problems involving pulleys in another, and problems involving friction in a third. This is significant in view of the fact that, depending on what is being asked, two problems involving inclined planes could require entirely different strategies for solution (e.g., one might involve kinematics to determine the time required for an object to slide down the plane, while another might involve conservation of energy to determine the final velocity of an object that rolls down the plane without slipping). The point is similarly made for problems involving pulleys or friction. Alert to such qualitative distinctions, experts displayed a strong inclination toward using the physical principle involved in solving the problem as the criterion for sorting it. For example, experts placed problems that could be solved by conservation of energy in one pile, problems that could be solved by Newton's Second Law in another, etc.

The important question arising from these findings, again, is whether novices will make more rapid and certain progress toward expert status if, in school, they are guided to think the way that experts do when they tackle a problem. If we find that the answer is "yes," this would complement previously cited findings about improved performance of novices when they were helped to organize knowledge in an expert-like hierarchical fashion. Thus far, a couple of studies suggest an affirmative answer. In one study,[28] novices were trained to generate a problem analysis before undertaking solutions. These analyses required novices to describe problems in terms of concepts, principles, and procedural strategies. The study showed that given this kind of preparation, students were better able to construct problem solutions.

What this and other evidence discloses is that experts possess a number of tacit skills in problem solving that are now seldom taught explicitly in classrooms, such as the following:

- Describing a problem in detail before attempting a solution.
- Determining what relevant information should go into the analysis of a problem.
- Deciding which procedures can be used to generate a problem description and analysis.

The strong implication is that useful learning will increase if students are explicitly taught these skills and challenged to apply them to work in the classroom.

To examine this assumption further, the authors and several colleagues at the University of Massachusetts recently conducted a multi-faceted study[29-31] focusing on the question of whether one can promote expert-like behavior in novices by structuring their problem-solving activities to reflect the hierarchical way in which physics experts analyze problems. Unlike previous studies which focused on specific topics (e.g., Newton's Second Law[13,27]), we were interested in ascertaining whether it was possible to affect novice-to-expert shifts across a wide range of physics topics. We therefore designed and developed a computer-based, expert-like problem analysis environment called the Hierarchical Analysis Tool (henceforth, HAT) that could be used to analyze the majority of problems in a calculus-based freshman classical mechanics course.

To analyze a problem using the HAT, the student answers well-defined questions by making selections from menus that are dynamically generated by computer software. In the first menu, the student selects a general principle that could be applied to solve the problem under consideration. Subsequent menus focus on ancillary concepts and procedures and are dependent upon the prior selections made by the student. The analysis is termed "hierarchical" because the menus become increasingly specific as one progresses. When the analysis is complete, the HAT provides the student with a set of equations that is consistent with the analysis conducted by the student. If the analysis is carried out incorrectly, the final equations are consistent with the student's menu selections but are inappropriate for solving the problem.

Thus the HAT is a flexible, self-consistent tool designed to constrain its user to apply a hierarchical, top-down, problem-solving approach. It is important to note that, because it was designed as a research tool and not as a pedagogical instrument, the HAT neither tutors nor provides feedback to the student. The user is therefore free to follow any path through the analyzer. Figure 6 contains the menus and selections that would appropriately analyze the energy problem given at the bottom of the figure.

In our study, subjects underwent a "treatment" consisting of solving 25 classical mechanics problems over five, one-hour sessions using the HAT. Two control groups were used for comparison purposes: one solved the treatment problems using the textbook as a resource, while the other solved the problems using a novice-like, computer-based environment called the Equation Sorting Tool (EST). The EST was a computer-based "formula-sheet" containing 178 equations taken from the textbook; this equation data-base could be searched and sorted via surface feature terminology (e.g., by problem types such as "inclined plane problems," by variable names such as "velocity," or by physics terms such as "potential energy").

The effectiveness of the HAT was compared against that of the two control treatments using three measures: 1) A problem-categorization task in which students were asked to match problems on the basis of the similarity of the approach that could be used to solve them, 2) An explanations task requiring that students provide written explanations of what would happen when a particular change was made in a given physical situation, and 3) A problem-solving task that resembled a final exam in a mechanics course. All three tasks were administered both

1 Which principle applies to this part of the problem solution?

1. Newton's Second Law or Kinematics
2. Angular Momentum
3. Linear Momentum
4. Work and Energy

Please enter your selection: [4]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

2 Describe the system in terms of its mechanical energy

1. Conservative system (conservation of energy)
2. Non-Conservative system (work-energy exchange)

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

3 Describe the changes in mechanical energy. Consider only the energy of one body at some initial and final state

1. Change in kinetic energy
2. Change in potential energy
3. Change in potential and kinetic energies

Please enter your selection: [3]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

4 Describe the changes in kinetic energy

1. Change in translational kinetic energy
2. Change in rotational kinetic energy
3. Change in translational and rotational kinetic energies

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

5 Describe the boundary conditions

1. No initial translational kinetic energy
2. No final translational kinetic energy
3. Initial and final translational kinetic energies

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

6 Describe the changes in potential energy

1. Changes in gravitational potential energy
2. Changes in spring potential energy
3. Changes in gravitational and spring potential energies

Please enter your selection: [1]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

7 Describe the boundary conditions

1. No initial gravitational potential energy
2. No final gravitational energy
3. Initial and final gravitational energy

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

8 Is there another body in the system which has not been examined?

1. Yes
2. No

Please enter your selection: [2]

(B)ackup (M)ain menu (G)lossary (Q)uit (L)ist selections

9 The Energy Principle states that the work done on the system by all non-conservative forces is equal to the change in the mechanical energy of the system:

$$W_{nc} = E_f - E_i$$

According to <u>your</u> selections,

$W_{nc} = 0$ (Conservative system: mechanical energy conserved)

$E_f = (\frac{1}{2}Mv^2)_{1f}$

$E_i = (Mgy)_{1i}$

Please press any key to continue

10 *** Work and Energy ***

1. Problem solved
2. Return to Main Menu to continue solution
3. Review previous solution screens

Please enter your selection:

Problem 1

A small block of mass M slides along a track having both curved and horizontal sections as shown. If the particle is released from rest at height h, what is its speed when it is on the horizontal section of the track? The track is frictionless.

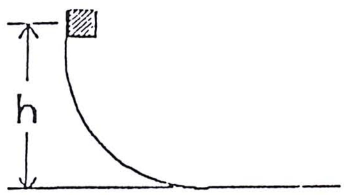

Fig. 6. Hierarchical analyzer menus and choices for problem 1.

before and after treatment; hence we were able to observe shifts in performance that resulted from the treatment.

The study yielded a number of interesting results:

- The categorization task showed that users of the HAT shifted significantly from categorizing problems on the basis of surface features toward categorizing on the basis of governing principles. Students in the control groups exhibited no such shift.
- After using the HAT, students used a widely applicable higher-order concept, energy, in a significantly fuller and more organized fashion in the explanation task.
- All three groups exhibited statistically significant improvements in the problem-solving task, although no single group improved significantly more than any other group.
- Despite the hunt and peck character of the EST, it was possible to use that environment in a hierarchical way by sorting the equation data base according to terms which were principles (e.g., conservation of energy) rather than variables (e.g., velocity) or problem types (e.g., inclined plane). The EST users who did this in a consistent manner were also, almost without exception, those who performed better on the explanation tasks. These were also the EST users who, by and large, performed best on the problem-solving pre- and post-tests.
- Although the overall correlation was not statistically significant, those students showing greatest pre-

to-post improvement on the explanation task also averaged well above mean improvement on the problem-solving test.
- For all three groups of students on both pre- and post-tests, correct identification of the governing principle(s) relevant to constructing a problem's solution was a necessary and substantial step in developing a correct solution strategy.
- In the explanation task, the context, shaped by the surface features of a given situation, strongly affected which variables students chose to discuss and which principles they applied, leading them to treat differently situations that physicists would consider analogous. For instance, students were more likely to consider gravitational potential energy, mgh, in a situation where the height, h, is altered than in one where g was changed by relocating a set-up to the moon.

What does all this mean for the teacher? To us, the data has several implications for the classroom:
- Since the HAT approach did promote greater shifts toward expertise than the two control approaches, our study suggests that the development of students' physics knowledge and problem-solving skills can be facilitated through activities in which students actively engage in structured problem-solving tasks that highlight the interplay of concepts and procedures.
- Our findings suggest that we should not rely on pencil-and-paper problem solving as the sole measure of our students' level of expertise. Tasks involving problem categorization and qualitative explanations can provide teachers with independent measures of students' understanding of physics. Our findings indicate that the improvements shown by HAT users surpassed that of the control groups for categorization and explanation, but not for problem solving. We interpret this to mean that, at least in the short term, problem solving is a less sensitive measure of the development of a student's knowledge of physics than are categorization and explanation. Aspects of these latter tasks must be combined with other elements, such as strategy formulation, mathematical knowledge, manipulative skills, and visualization skills, in the more complex task of solving a problem. Thus, we should expect neither that problem-solving measures are the most precise measures of expertise, nor that the ability to do well in problem-solving measures necessarily implies a deep conceptual understanding of physical situations.
- The fact that students show context dependence in the application of concepts to situations that physicists would consider analogous suggests that we need to diversify the students' experiential base, as well as to teach them a structure for organizing it. The type of thinking that proceeds from governing principles rather than surface features requires, in part, the ability to recognize when a principle is applicable, that is, to have a sense of its *range* of applicability. Organization becomes valuable only when there is enough stored in the student's memory to make it efficient to organize the knowledge (i.e., you can't meaningfully order a deck of only two cards). We believe that most good teachers know how to help students expand and structure their knowledge base. When teaching a concept, good teachers help students explore the ramifications of the concept through a diversity of examples that explore the range of the concept's applicability.

Concluding Remarks

We are addressing our remarks about cognitive research directly to physics teachers because we believe that in the long run the findings will have impact only if they are useful in the classroom. Of course, most of the work cited is still relatively recent, mostly less than ten years old. Although the field of cognition and instruction is young, we hope that we have demonstrated a level of maturity in the research findings that suggests their readiness for testing and evaluation through practical classroom application. What we must hope for now is increased collaboration between teachers and researchers, especially in the design of instructional approaches that integrate process and content.

We are not naive about major obstacles that stand in the way of improving the climate of inquiry in our classrooms. Textbook design continues to emphasize breadth of content coverage, rote learning, and quantitative rather than qualitative reasoning.[32] Added to this, most available assessment instruments largely measure a student's command of factual and quantitative knowledge. A recent review of selected science achievement tests conducted under the auspices of the National Research Council revealed that, with few notable exceptions, test items did little to assess higher-order thinking skills.[33] This view was echoed by a study commissioned by the National Science Foundation to identify NSF initiatives that could be pursued to address problems and opportunities in K-12 science education; one recommendation was to improve science testing instruments.[34] The teacher who wants to help students engage and acquire skill in serious inquiry is in a difficult situation. If prescribed textbooks provide little occasion for practice in needed skills, and tests largely ignore them in measuring student achievement, the teacher will find little support in emphasizing intellectual processes within the context of content. Obviously, this is another closed circle that must be broken.

A major change in the way that physics is taught in our schools would require the cooperation and imagination of teachers and teacher organizations, parents, researchers, school administrators, test developers, and textbook pub-

lishers. But no major movement aimed at improving classroom instruction can be successful unless it is sustained by the day to day practices of the classroom teacher. There may or may not be major strides toward marrying content and process in our education system. However, there is one thing that we are guaranteed of having if a few teachers make a concerted effort to deal actively with cognitive processes in their classrooms: more students who will be able to bring an *understanding* of physics to bear on non-routine situations. ♦

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